AN OVERVIEW OF SMOKE CONTROL RESEARCH

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ABSTRACT

In commemoration of the ASHRAE Centennial, this paper is a brief overview of research relating to smoke control. This paper describes many significant smoke control research and related efforts from 1972 to the present. These projects are discussed in this paper with the intent of providing information about smoke control systems and the underlying principles behind them. A secondary goal of the paper is to develop an appreciation of the effort required to advance the technology of these systems. The two main categories of smoke management systems used in buildings are pressurization systems and exhaust systems for atria (and other large spaces). In general, this paper addresses the pressurization systems and related efforts.

INTRODUCTION

The evolution of smoke control technology has involved contributions from code officials, firefighters, fire protection engineers, mechanical engineers, researchers, and other professionals. Some early papers discussing system concepts were written by Fung (1976), Hobson and Stewart (1973), McGuire (1967), and McGuire and Tamura (1971). For current information about the design and analysis of smoke management systems, refer to the ASHRAE smoke control design book (Klote and Milke 1992).

In commemoration of the ASHRAE Centennial, this paper is a brief overview of research relating to smoke control. There have been so many smoke control research efforts that it is impossible to address them all in one paper. However, some significant smoke control research and related efforts are listed in Table 1, and Figure 1 is an approximate time line of these efforts.

Scientists consider research to be an investigation into a subject in order to gain or improve an understanding of that subject, and research involves theories and experiments. However, in keeping with common usage at ASHRAE, the term *research* is used in this paper to include engineering studies and tests. This includes tests that have no theoretical analysis.

The two main categories of smoke management systems used in buildings are pressurization systems and exhaust systems for atria (and other large spaces). In general, this paper addresses the pressurization systems and related efforts. However, one atrium project was included in Table 1 because that project was funded by ASHRAE. Additionally, airflow has been used with the intention of preventing smoke flow through open doors, and this topic is discussed including the concern of supplying combustion air to the fire.

PRESSURIZATION CONCEPT

Pressurization has been used for much of this century to protect against the spread of biological and chemical contaminants in a variety of applications, including hospital operating rooms and laboratories. In the last two decades, pressurization also has been used to control against the spread of smoke due to building fires. Systems using pressurization produced by mechanical fans are referred to as smoke control systems in NFPA 92A (NFPA 1993) and in the ASHRAE smoke control design book.

A pressure difference across a barrier can control smoke movement, as illustrated in Figure 2. Within the barrier is a door. The high-pressure side of the door can be either a refuge area or an egress route. The low-pressure side is exposed to smoke from a fire. Airflow through the gaps around the door and through construction cracks prevents smoke infiltration to the high-pressure side.

Later in this paper several full-scale fire tests of smoke control systems are discussed. Each of these series of tests was unique in that different types of smoke control systems were studied in different kinds of occupancies. However, all showed that pressure differences can prevent smoke migration from the low-pressure side to the high-pressure side of a barrier. This holds for pressure differences as small as 2 Pa (0.01 in. H_2O). To be effective, a smoke control system must produce pressure differences in the desired direction under fire conditions. Fires increase pressures due to the buoyancy of hot gas, and building pressures fluctuate due to changes in barometric pressure, wind, doors opening, doors closing, and system controls. To account for these and to allow a safety factor, NFPA 92A indicates that smoke control systems must maintain the pressure differences listed in Table 2.

HENRY GRADY TESTS

The Atlanta City Building Department conducted a series of full-scale fire tests of smoke control systems in the Henry Grady Hotel (Koplon 1973a, 1973b). The 14-story

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TABLE 1
Some Smoke Control Research and Related Efforts

Project/Organization	Topics Studied	Methods
Henry Grady Hotel Tests[1] Atlanta City Building Dept.	Stairwell Pressurization and Elevator Pressurization	Full Scale Fires
Church Street Office Building[2] Tests Brooklyn Polytechnic Institute	Stairwell Pressurization	Full Scale Fires
Pressure Losses in Shafts[3] NRCC	Leakage Areas of Shafts and Friction Losses in Stairwells	Field Tests
Hamburg Office Building Test[4] Fire Check Consultants	Stairwell Pressurization and Lobby Pressurization	Full Scale Fire
Huggett's Constant[5] NBS	Oxygen Consumption	Theoretical Study
ASHRAE Smoke Control[6] Manual NBS	Systems Concepts and Design Methods	Engineering Study
Validation of Network Models[7] NBS/CSTB	Airflow Due to Stairwell Pressurization	Full Scale Tests
Joint Elevator Project[8] NBS(later NIST)/NRCC	Systems Concepts, Piston Effect, and Design Information	Theoretical Study, Field Tests, and Full Scale Fires
Pressure Losses in Stairwells[9] NRCC	Friction Pressure Losses	Full Scale Tests
Stairwell Systems Project[10] NRCC	Overpressure Relief and Mechanical Venting	Airflow Tests and Full Scale Fires
Plaza Hotel Project[11] NIST	Zoned Smoke Control and Stairwell Pressurization	Theoretical Study and Full Scale Fires
Revise ASHRAE Manual[12] NIST	Systems Concepts and Design Methods	Engineering Study
Sprinkler Effect Project[13] NRCC	Impact of Sprinklers on Smoke Control	Full Scale Fires
Evaluate Network Algorithms[14] G.K. Yuill & Assoc.	Search for Reliable Algorithm for Networks	Computer Study
Atrium Algorithm Project[15] Univ. of Maryland	Design Analysis of Atrum Exhaust Systems	Theoretical Study
Fire Damper Study[16]	Fire Dampers Under Flow and High Temperature	Laboratory Study
Wind Data Project[17]	Wind Data for Smoke Control Systems	Computer Study

[1]Koplon (1973a, 1973b).
[2]DeCicco (1973) and Cresci (1973).
[3]Tamura and Shaw (1976).
[4]Butcher et al. (1976).
[5]Huggett (1980).
[6]Klote and Fothergill (1983).
[7]Klote and Bodart (1985).
[8]Klote and Tamura (1986a, 1986b, 1987, 1991), Tamura and Klote (1987a, 1987b, 1988), Klote (1988).
[9]Achakji and Tamura (1988).
[10]Tamura (1990a, 1990b).
[11]Klote (1990).
[12]Klote and Milke (1992).
[13]Mawhinney and Tamura (1994).
[14]Wray and Yuill (1993).
[15]Milke and Mowrer (1994).
[16]Final report being written.
[17]Ongoing project.

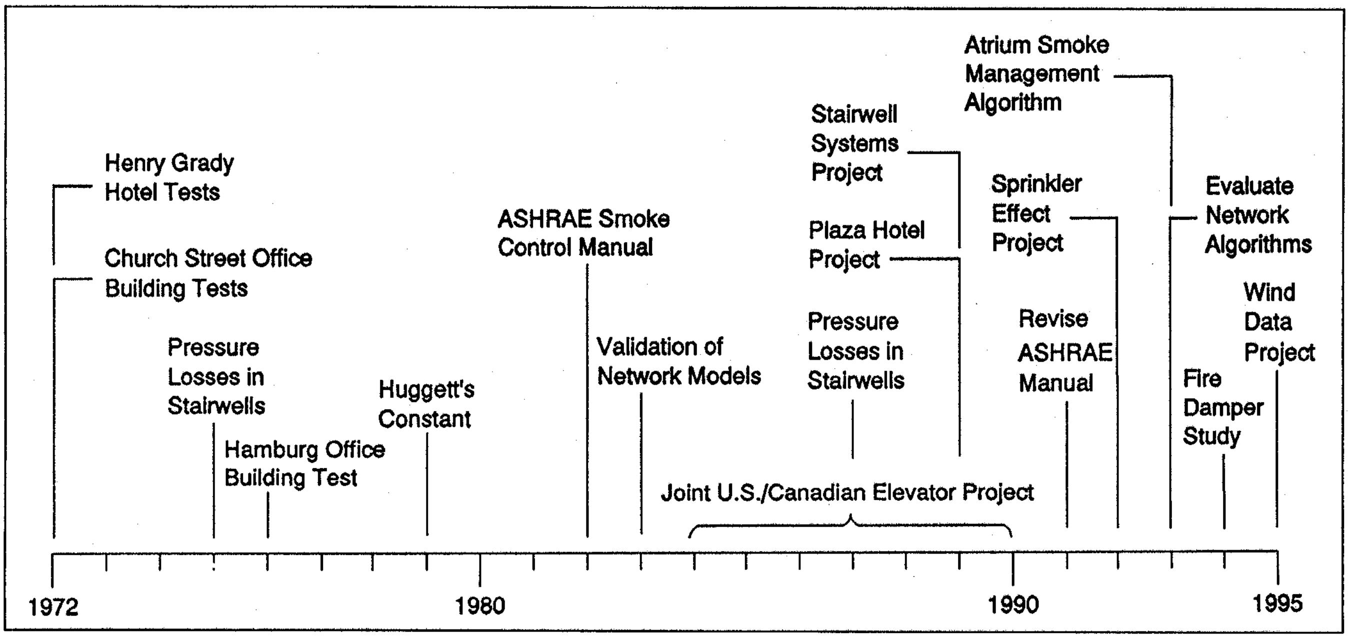


Figure 1 *Approximate time line of smoke control research and related efforts.*

building was made available for the tests by the firm of John Portman and Associates, and afterward the building was demolished.

The purpose of the tests was to evaluate the effectiveness of the following smoke control systems: stairwell pressurization without vestibules, stairwell pressurization with vestibules, and elevator hoistway (shaft) pressurization. The stairwell systems were intended to provide "smokefree" egress, and the elevator system was intended to prevent smoke movement through the hoistway. The design of these smoke control systems was based on the latest papers and ideas about the topic.

Fire tests without vestibules were staged on floor 3 and fire tests with vestibules were staged on floor 5, as illustrated in Figure 3. The fires consisted of materials that would be expected to be in a hotel room. For example, beds with mattresses, wood chairs, draperies, lamps, and chests of drawers.

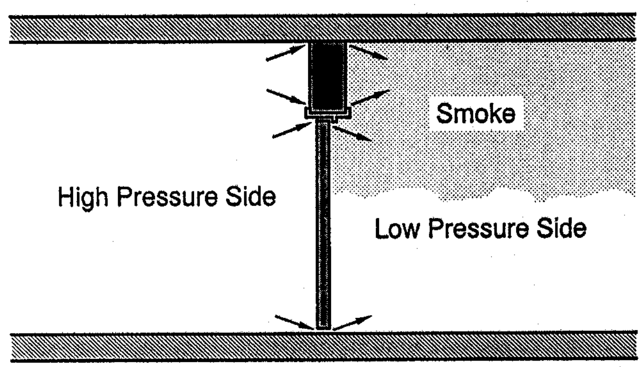


Figure 2 *Pressure difference across a barrier preventing smoke infiltration to the high-pressure side of the barrier.*

TABLE 2
Minimum Pressure Design Difference (adapted from NFPA 1993)

Building Type[2]	Ceiling Height		Design Pressure Difference	
	m	ft	Pa	in H_2O
AS	Any	Any	12.4	0.05
NS	2.7	9	24.9	0.10
NS	4.6	15	34.8	0.14
NS	6.4	21	44.8	0.18

[1]For design purposes, a smoke control system should maintain these minimum pressure differences under likely conditions of stack effect or wind.
[2]AS for sprinklered and NS for nonsprinklered.

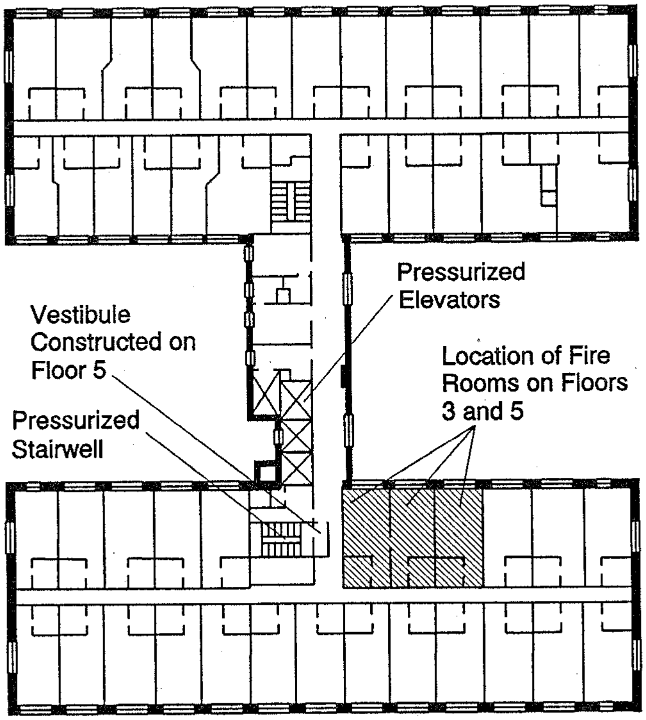


Figure 3 *Typical floor plan of the Henry Grady Hotel.*

Most of the instrumentation was installed and operated by the National Bureau of Standards (NBS) (now the National Institute of Standards and Technology [NIST]) and the Georgia Institute of Technology. Temperature, radiative heat flux, smoke obscuration, carbon monoxide concentration, and pressure difference were measured and reported for many locations. The impacts of these data on smoke control were discussed. The project demonstrated that pressurization could provide "smokefree" exits for the fire scenarios and systems tested.

CHURCH STREET OFFICE BUILDING TESTS

At about the same time as the Henry Grady tests, the Brooklyn Polytechnic Institute conducted a series of fire experiments at a 22-story office building on Church Street in New York City (DeCicco 1973). This building was also scheduled for demolition.

These tests studied the effectiveness of stairwell pressurization systems. Four fires were set at the locations on the seventh and tenth floors shown in Figure 4. The first two tests were conducted to verify the operation of the stairwell pressurization system with conditions of elevated temperature and elevated pressure due to the fire. Tests three and four studied fire through ceiling spaces. Test four studied stairwell pressurization in conjunction with fire-floor exhaust.

The materials burned were representative of fuels that would be in an office, for example, desks, chairs, considerable paper on the desks, and boxes of paper. Temperatures and pressure differences were measured. Tests were also conducted on the effect of open doors on the performance of the pressurized stairwell. As with the Henry Grady tests, this project demonstrated that pressurization could provide "smokefree" exits for the fire scenarios and systems tested.

This project was different from the Henry Grady project in that a theoretical model of shaft airflow was developed, and airflow and pressure measurements were made in the building stair to evaluate that model. Also, a scale model of the stair shaft at the Church Street building was constructed by Cresci (1973), and a systematic series of experiments were conducted. Cresci describes visualization experiments where stationary vortices were observed at open doorways. These vortices are the reason why the flow coefficient through an open stairwell door is about half of what it would be otherwise. This has such a significant effect on airflow in stairwells that it is incorporated in current design analyses (Klote and Milke 1992).

HAMBURG OFFICE BUILDING TEST

The fire test of April 4, 1976, at a seven-story office building in Hamburg, Germany, was not intended to be research but was part of the new building's acceptance tests. This test is discussed here because it was probably the first time that a smoke control system in a new building had been tested by a full-scale fire (Butcher et al. 1976).

This unique acceptance test was indirectly the result of a piece of property being too small for economical construction of a conventional office building. If the largest building that could be built on the property had two stairs, the owner indicated that the building cost per unit area of rentable floor space would be unacceptably high. However, a building with one stairwell would be economical. The Hamburg fire ser-

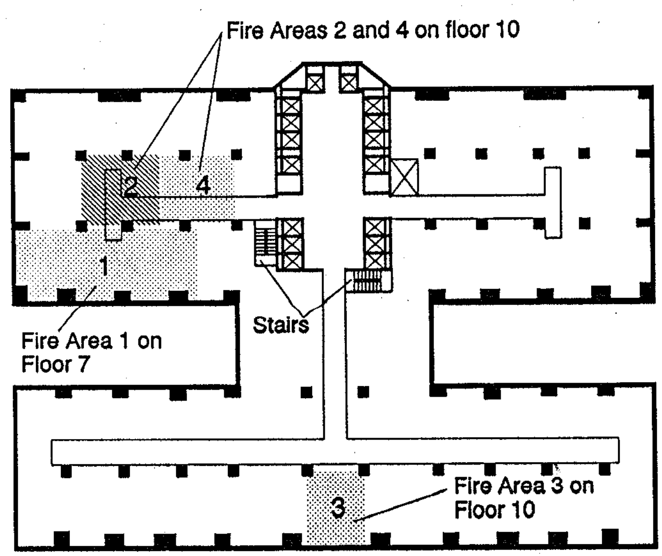


Figure 4 *Typical floor plan of 30 Church Street office building.*

vice agreed that, for this building, a pressurized stairwell with a pressurized lobby (Figure 5) would be an acceptable alternative to two stairwells, provided the smoke control system passed a full-scale fire test.

The fire was in a second-floor office, and the fuel consisted of wood cribs and slabs of expanded polystyrene weighing a total of 370 kg (810 lb). Wood cribs are a geometrically arranged pile of sticks, as shown in Figure 5. Crib fires are repeatable, as opposed to fires of discarded furniture and the other materials used in the earlier tests.

Temperature, airflow, smoke obscuration, carbon monoxide concentration, carbon dioxide concentration, and pressure difference were measured at many locations. The maximum temperature reached in the burn room was 700°C (1290°F) at 17 minutes after ignition. The fire was extinguished 35 minutes after ignition. During this test, various combinations of stair, lobby, and office doors were opened and closed on floors away from the fire floor. Throughout the tests the stairwell and the lobby were recorded as "smokefree," except for about 2 minutes at the peak of the fire, when there was 30% smoke obscuration in the lobby on the fire floor. As with the Henry Grady and Church Street tests, this project also demonstrated that pressurization could provide "smokefree" exits for the fire scenarios and systems tested.

SMOKE CONTROL DESIGN BOOK

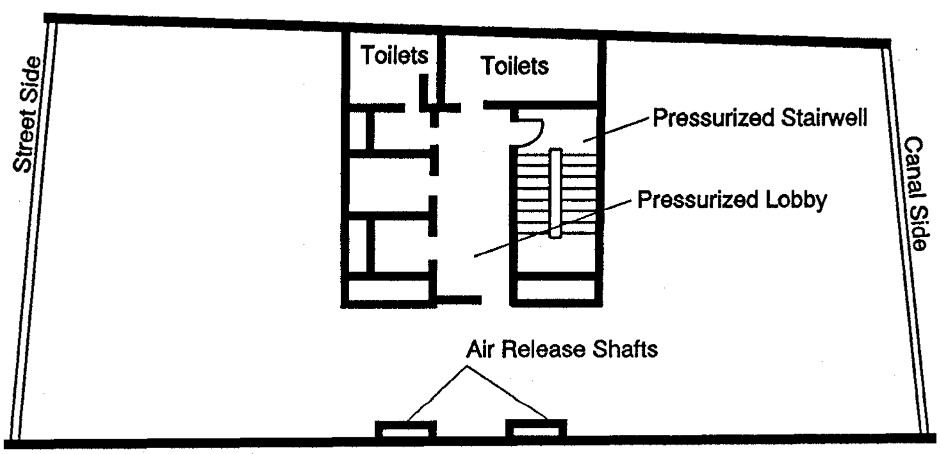
Due to the need for organized smoke control design information, an ASHRAE research project was established to develop a smoke control book. In addition to the research discussed above, the book was based on work at the NBS and the National Research Council of Canada (NRCC). Francis Fung and later John Klote conducted numerous smoke control projects at NBS, including field tests, computer analyses, and conceptual studies. George Tamura and his associates at the NRCC conducted similar research and established a base of experimental data about the leakage of commercial buildings. The resulting book, *Design of Smoke Control Systems for Buildings* (Klote and Fothergill 1983), addressed fundamental concepts, computer analysis of smoke control systems, stairwell pressurization, zoned smoke control, and acceptance testing. Engineers finally had the ability to design smoke control systems based on the principles of engineering. This book was extensively revised and expanded as *Design of Smoke Management Systems* (Klote and Milke 1992).

NETWORK COMPUTER MODELS

The flows in buildings with pressurization systems are very complicated, and it is an understatement to say that these flows are not well suited to hand calculation. For this reason computer programs have been developed to model the airflow in buildings with these systems. Some programs calculate steady-state airflow and pressures throughout a building (Sander 1974; Sander and Tamura 1973). Other programs go beyond this to calculate the smoke concentrations that would be produced throughout a building in the event of a fire (Yoshida et al. 1979; Butcher et al. 1969; Barrett and Locklin 1969; Evers and Waterhouse 1978; Wakamatsu 1977).

The ASCOS program was intended specifically for analysis of pressurization smoke control systems (Klote and Fothergill 1983). ASCOS is the most widely used program for smoke control analysis (Said 1988) and it has been validated against field data from flow experiments at an eight-story tower in Champs Sur Marne, France (Klote and Bodart 1985).

ASCOS and the other network models have been used extensively for design and for parametric analysis of the performance of smoke control systems. However, ASCOS was



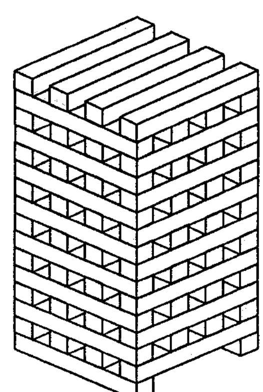


Figure 5 *Typical floor plan of Hamburg office building and arrangement of wood cribs burned.*

originally intended as a research tool for application to 10- and 20-story buildings. It was not surprising that convergence failures were encountered with some applications to much taller buildings.

An ASHRAE-funded project evaluated several flow algorithms to find the most appropriate one for analysis of smoke control systems (Wray and Yuill 1993). The AIRNET flow routine developed by Walton (1989) was selected as the best algorithm based on computational speed and use of computer memory. None of the algorithms evaluated in this study has user-friendly data input that takes advantage of the repetitive nature of building flow networks. However, Walton (1994) has developed the CONTAM93 program with an improved version of the AIRNET flow routine and with friendly input.

PRESSURE LOSSES IN STAIRWELLS

The pressure losses in pressurized stairwells or elevator shafts are important to system performance, and many computer network models can simulate these losses. Building on Cresci's study of shaft flow, Tamura and Shaw (1976) studied leakage areas of shaft walls and friction losses due to shaft flow. They conducted field tests of pressure losses in eight stairwells using portable fans to generate shaft flow. They showed that these losses could be analyzed by a model similar to that for friction losses in ducts. This project resulted in limited data for computer analysis.

This work was expanded when Achakji and Tamura (1988) conducted experiments in the stairwell of a 10-story experimental tower (discussed later). Tests were done under various conditions, including with open stair treads, with closed stair treads, without occupants, and with various occupancy densities simulated by standing cylindrical tubes (0.31 m [1 ft] diameter by 1.8 m [5.9 ft] high) in the stairwell. Some tests were also conducted using people in the stairs to verify the use of tubes. The data were analyzed using their duct loss model, and Achakji and Tamura developed a table of loss coefficients for various stair conditions.

EXPERIMENTAL FIRE TOWER

In the mid-1980s, the NRCC built a 10-story research tower near Ottawa for the purpose of full-scale fire experiments of smoke control systems. Figure 6 is a typical floor plan of the tower. The experimental tower is connected to a service tower that has space for researchers to observe experiments in safety. The core of the experimental tower consists of stairs, an elevator shaft, a lobby, and seven air shafts to allow simulation of many different stairwell and elevator smoke control systems. The shafts are connected through a tunnel to a remote building where supply fans are located. Exhaust fans are located on the roof of the experimental tower.

The experimental tower is instrumented to measure temperature, airflow, smoke obscuration, gas concentrations, and pressure differences at many locations on each floor. Gas analysis includes oxygen, carbon monoxide, and carbon dioxide. Data-acquisition boxes are located on even floors of the service tower, and these boxes are connected to a minicomputer (located in another building) that is connected to the service tower at the first floor. During experiments, data are collected by the data-acquisition boxes and transferred to the minicomputer. After the experiments, data are reduced and analyzed on the minicomputer.

The setup for measurement of pressure difference and gas concentration has resulted in steady-state experiments. This can be explained by considering the gas analysis. Tubes are used to pull gas from points in the experimental tower to the service tower. Several tubes are connected to a manifold of solenoid valves that feeds into a gas analyzer. The manifold sequentially connects each tube to the gas analyzer so that, at any time slice of the data-acquisition system, the gas concentration is measured from only one measurement point. Several time slices are required to make one reading at each point. The pressure difference measurements are similar. Thus the experimental setup was developed specifically for steady-state experiments.

Gas burners were selected as the fire source for the tower (Figure 6) because they are more repeatable and more easily controlled than cribs. To prevent dangers resulting from unburned gas, air is premixed with the gas before it reaches the burners. To prevent unwanted pressurization due to the premixed air, most experiments are conducted with openings in the exterior walls of the fire floor simulating broken fire-floor windows.

Joint NIST/NRCC Elevator Project

The first project to use the experimental fire tower was a joint NIST/NRCC project to study the feasibility of elevator

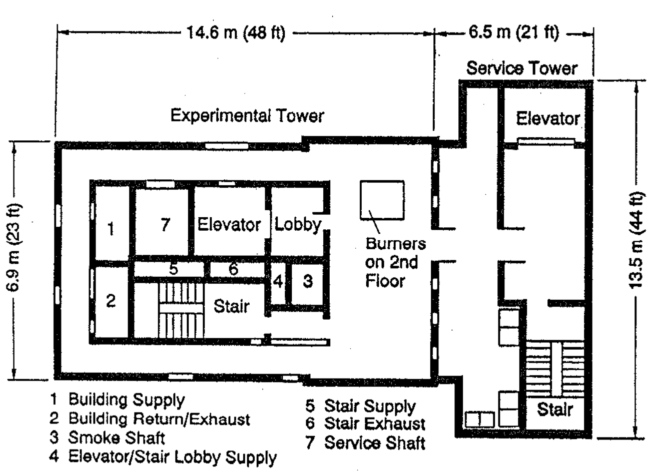


Figure 6 *Typical floor plan of the experimental fire tower near Ottawa.*

smoke control. Some people cannot use stairwells because of physical disabilities, and the use of elevators is a potential method to provide life safety for these people. For an elevator system to be used for fire evacuation, that system must have protection from heat, flame, smoke, water, overheating of elevator machine room equipment, and loss of electrical power. For more information about the general topic of elevator fire evacuation, readers are referred to Klote et al. (1994).

Full-scale fire experiments were conducted in the experimental fire tower (Tamura and Klote 1987a, 1987b, 1988). The flow areas within the tower were set so that they were representative of leakage areas of buildings based on field measurements of building leakage conducted at the NRCC. The systems were tested against gas burner fires on the second floor, and these tests verified that pressurization can provide smoke protection for the elevator system.

In addition to the work at the experimental fire tower, the project also addressed the impact on smoke control of pressure disturbances caused by elevator car motion (Klote and Tamura 1986a, 1986b, 1987; Klote 1988). Such piston effect is a concern because it can pull smoke into a normally pressurized elevator lobby. An analysis of elevator piston effect was developed from basic principles of engineering. Experiments were conducted with elevators at NIST's 11-story administration building to evaluate the flow coefficients for airflow around an elevator car. Piston effect experiments were conducted on an elevator of a hotel in Mississauga, Ontario, Canada. Using the coefficients developed from measurements on the NIST building, the trends of the calculated pressure differences were in good agreement with the experimental results (Figure 7). Based on this piston effect theory, a simple design approach was developed to ensure that elevator smoke control performance is not adversely affected by piston effect.

The information learned from this project was consolidated in a paper discussing piston effect, elevator smoke control system concepts, pressure changes due to doors opening and closing, and design approaches to deal with these pressure changes (Klote and Tamura 1991). This paper had an example design analysis using the network computer program ASCOS. While some of the experiments of this project addressed wind effects, development of methods of analysis incorporating wind effects was beyond the scope of the joint project. However, a method of wind analysis for smoke control design was developed by Klote (1993), including an example design analysis using ASCOS. The information in that paper is applicable to elevator smoke control systems. An ongoing ASHRAE-sponsored research project is developing wind data for use in smoke control design.

Stairwell Systems Project

In this project, Tamura (1990a, 1990b) studied the performance of stairwell pressurization using a fan bypass system, a variable-speed fan system, and stairwell pressurization plus fan-powered venting of the fire floor. This project was sponsored in part by ASHRAE. These systems were developed by many smoke control designers over many years, and the general concepts behind them are discussed in the ASHRAE smoke control design book (Klote and Milke 1992).

Again, the flow areas within the tower were set so that they were representative of leakage areas of buildings based on field tests of building leakage conducted at NRCC. The

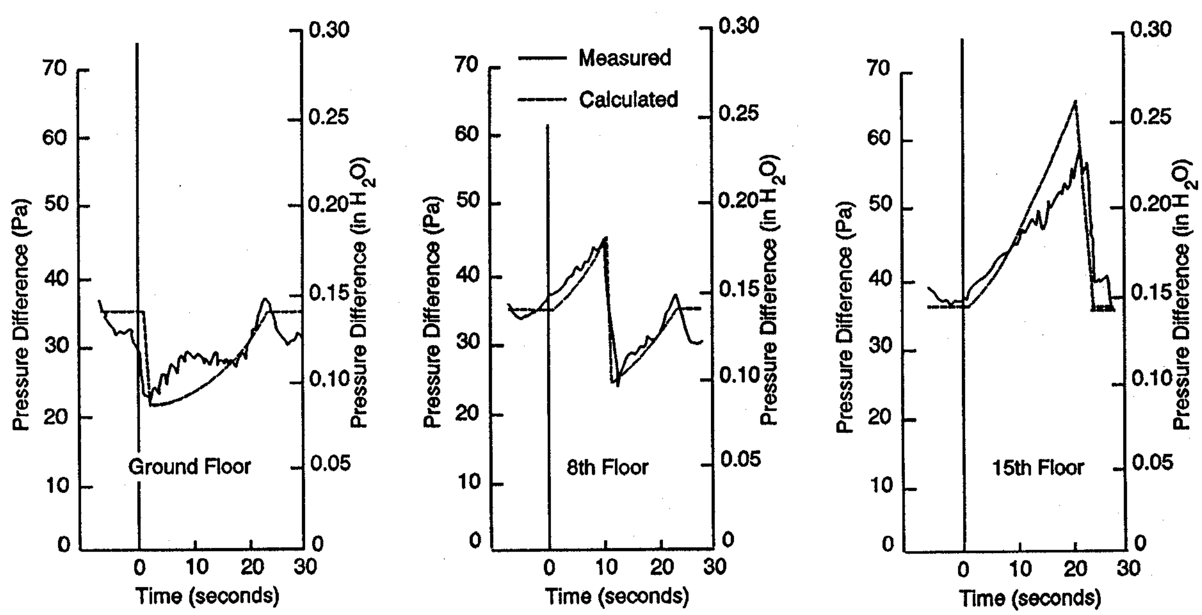


Figure 7 *Comparison of measured and calculated pressure difference due to the piston effect of an ascending car.*

fires also used the gas burners on the second floor. These tests verified much of the information about these systems gained by network computer analysis. For example, the systems were capable of preventing smoke infiltration to the stairwell when all the stairwell doors were closed and when a number of the stairwell doors away from the fire floor were opened. This number depends on the system type, the building leakage, and the outside temperature. For the fan bypass and variable-speed fan systems, this number was about two or three. For the system including fan-powered venting of the fire floor, the number was four. Deviations on these and other systems are capable of preventing smoke infiltration with a larger number of doors opened.

Figure 8 shows transient pressure differences of the fan bypass system for doors opening and closing. The transients of the variable-speed fan system are similar. The pressure drop following the opening of the second-floor stairwell door is a concern in that it lasted about six minutes and the pressure difference plunged to about 20% of the design value (Figure 8). During such a pressure drop, smoke might enter the stairwell. The transients following opening of the other doors shown in Figure 8 were of much smaller drop and duration. One approach to limiting smoke flow into stairwells during these transients is to design systems that limit the pressure drops and the durations. For example, the pressure drops could be limited to 50% of the design value and a three-minute duration. Another approach consists of a hazard analysis including fire modeling and tenability calculations, as discussed by Bukowski et al. (1991).

It was not surprising that smoke usually flowed into the stairwell when the stairwell door was open on the fire floor during the NRCC tests. Using airflow in the open doorway to prevent such smoke backflow can have disastrous results due to the oxygen supplied to the fire. This topic is addressed later.

Sprinkler Effect Project

The NRCC conducted a series of full-scale fires to study the effects of sprinklers on zoned smoke control systems (Mawhinney and Tamura 1994). This project was funded in part by ASHRAE, and the tests were at the NRCC's burn hall and experimental fire tower. All of the fire tests discussed above were focused on unsprinklered fires because hot and buoyant smoke from unsprinklered fires is more difficult to control than that from sprinklered fires. The intent of this project was to provide information that could help evaluate the role of smoke control in sprinklered buildings.

Because the ability of sprinklers to extinguish unshielded fires is well established, this project addressed fires that could not be extinguished immediately by sprinklers and which would result in sustained smoke production. Wood cribs weighing 545 kg (1,200 lb) were burned in a one-story building in the burn hall, and cribs weighing 320 kg (700 lb) were burned in the tower. These cribs were made of 90 by 90 mm (3.5 by 3.5 in.) pieces of lumber. The top row of each crib was 90 mm (3.5 in.) thick solid lumber covered by 19-mm (0.75-in.) plywood. This construction prevented sprinkler water from reaching the crib interior, and the sprinkler fires could continue for an hour or more. In addition, these fires produced significant levels of carbon monoxide (as high as 2%).

As expected, the zoned smoke control system had no difficulty controlling smoke from these shielded fires. An unanswered question from this project is: To what extent are fires like this crib fire likely in residential and commercial

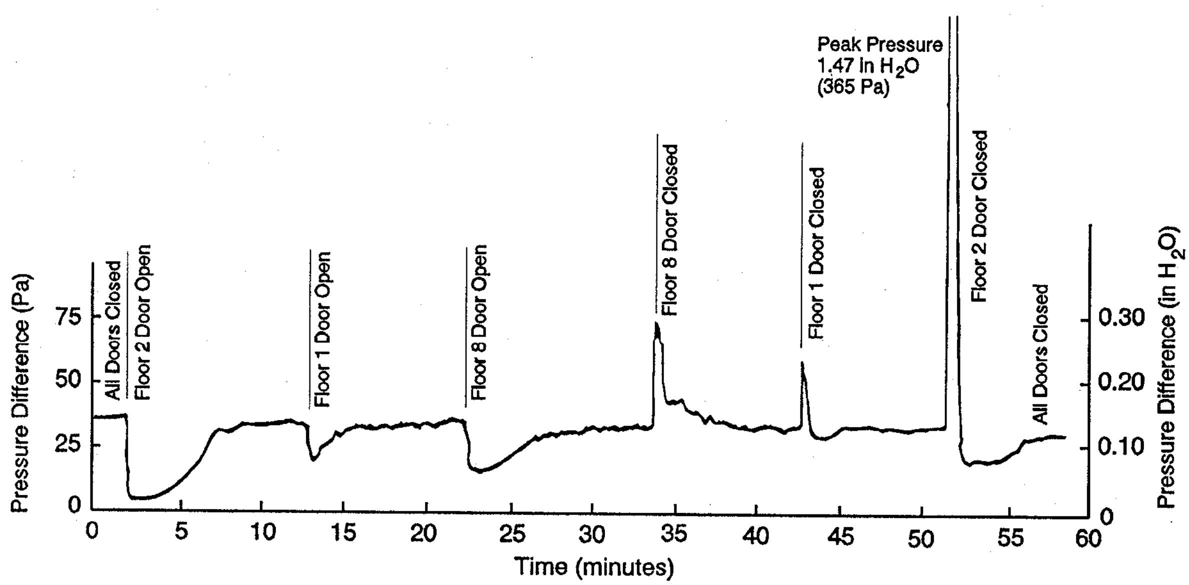


Figure 8 *Transient pressure differences produced at the NRCC experimental fire tower by a fan bypass stairwell pressurization system.*

buildings? Madrzykowski and Vettori (1992) evaluated data from many sprinklered fires, including shielded fires of many furniture arrangements and materials that are common to office buildings. They did not find any data for fuel arrangements of office furnishings that burned like the cribs used in the experiments conducted by Mawhinney and Tamura. The NRCC is engaged in a follow-up project (partly funded by ASHRAE) to determine to what extent there are fuels in nonindustrial buildings that burn like the crib fire above.

PLAZA HOTEL PROJECT

In the spring of 1989, NIST conducted a series of experiments of zoned smoke control at the Plaza Hotel in Washington, DC (Klote 1990). ASHRAE was one of the sponsors of this project. A zoned smoke control system is a system that uses pressurization to restrict smoke migration to the zone of fire origin. The benefit of these systems is that the other zones in the building remain "smokefree," thus reducing property loss and hazard to life.

The Plaza Hotel was a seven-story building built around the turn of the century, and it was scheduled to be demolished after this project. Fires were set at two locations on the second floor (Figure 9). An exhaust fan was installed to depressurize the fire floor, and other fans were installed to pressurize the stairwell and the floors above and below the fire floor. The design of these smoke control systems was based on designs in the ASHRAE smoke control book and NFPA 92A. The experiments demonstrated that these smoke control systems work as intended.

Because the interaction of the smoke control system and the fire was of interest, it was desired to burn solid fuels. For each fire, either two or four 68-kg (150-lb) wood cribs were burned (Figure 9). The building was instrumented for measurement of temperature, smoke obscuration, pressure difference, wind velocity, wind direction, and concentration of carbon monoxide, carbon dioxide, and oxygen.

An analysis based on first principles of engineering was made of the pressure differences produced by the smoke control system during the fires. The general trends of calculated values were in agreement with the measurements (Figure 10). Based on this analysis, the effect of fan temperature on smoke control system performance became apparent. Expansion of gases due to the fire can reduce the pressure differences at the boundary of the smoke zone. This reduction of pressure difference can result in decreased effectiveness of the smoke control system. An approach was developed to prevent system failure due to such reduced pressure differences.

For fire modeling, pressures within the fire spaces are considered hydrostatic, and this approach to pressure analysis is also commonly used in analysis of smoke control systems. Analysis of the Plaza Hotel data supported the use of the hydrostatic equation for both fire modeling and smoke control system analysis.

SMOKE FLOW AND OPEN DOORS

The performance of the pressurization systems discussed above was with doors closed in the smoke control barriers (walls). However, smoke flow through open doors has been the subject of considerable debate. The considerations about doors subjected to smoke apply to all smoke control systems that rely on pressurization but, for simplicity, the discussion will focus of stairwell pressuriza-

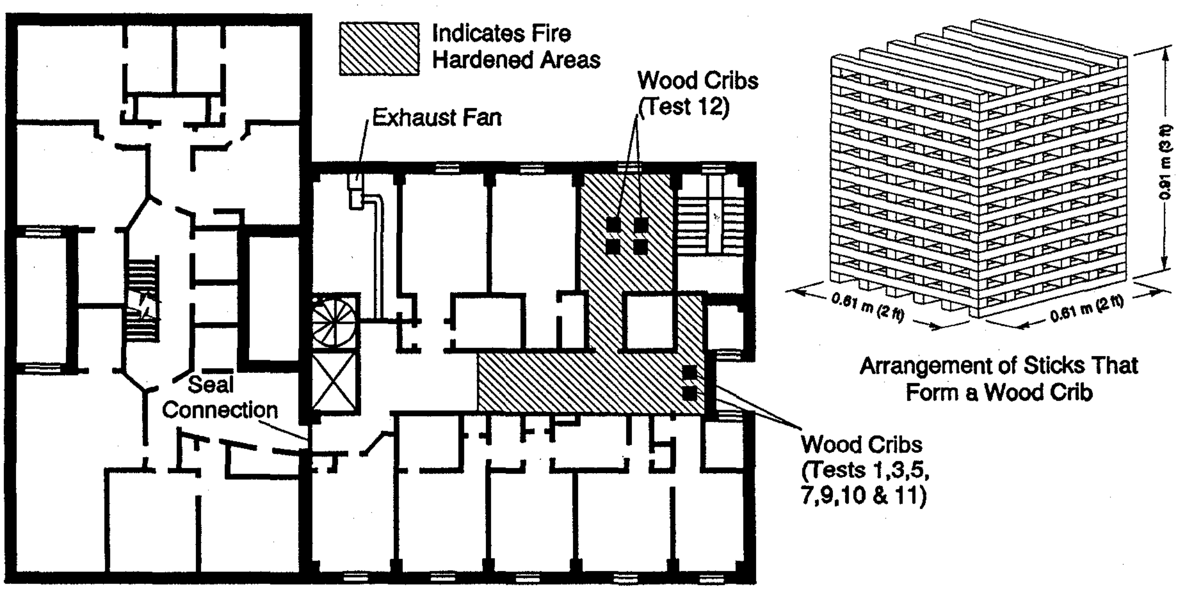


Figure 9 *Second-floor plan of Plaza Hotel.*

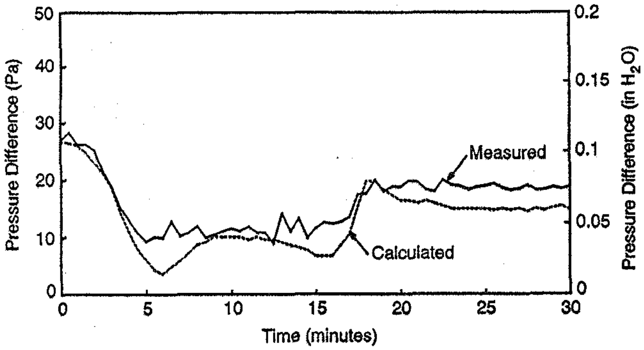


Figure 10 *Comparison of measured and calculated pressure differences of the pressurized stairwell on the fire floor of test 7 of the Plaza Hotel project.*

tion systems. The debate can be summarized by two positions: (1) airflow should be used to prevent smoke from entering stairwells on the fire floor, and (2) keeping doors closed is preferable to using airflow, which supplies oxygen to the fire. The following discussion relies on research results to evaluate the consequences of smoke control by airflow, and shows that for most building applications the second position is recommended, as stated later.

The following sections will show that using airflow to stop smoke from a specific fire from flowing through a stairwell doorway results in supplying enough air to the fire to increase the burning rate by a factor of 10. Considering the large amounts of permanent and transient fuel in most buildings, the danger of using airflow to control smoke is significant.

Stairwell doors are equipped with automatic closers and are normally closed, except for short times when people are coming into or going out of the stairwell. If a person on the fire floor opens a stairwell door, a small amount of smoke may enter the stairwell during an interval of a few seconds. However, this should not result in untenable conditions in the stairwell, considering that the person could travel through the smoke to get to the stairwell. If the smoke were untenable on the fire floor, people would not be able to get to the stair door to open it. If smoke enters a stairwell due to a door being blocked open, that stairwell should not be used for evacuation, and that stairwell pressurization system should be deactivated.

Critical Velocity

Reduced-scale experiments were conducted by Thomas (1970) to evaluate the airflow needed to prevent smoke from flowing upstream of a fire in a corridor. Heselden (1978) studied similar flow for tunnels. Rilling (1980) studied the mechanism and conditions of smoke control through a door opening. Tamura (1991) conducted a series of full-scale fires to determine the velocities needed to prevent smoke backflow at a stairwell door opening.

To illustrate the problem with airflow supplying oxygen to the fire, the relationship of Thomas can be used:

$$V_k = K_v\left(\frac{E}{W}\right)^{1/3} \tag{1}$$

where

V_k = critical air velocity to prevent smoke backflow (m/s [fpm]),
E = energy release rate into corridor (W [Btu/h]),
W = corridor width (m [ft]), and
K_v = coefficient (0.0292 [5.68]).

This relation can be used when the fire is located in the corridor or when the smoke enters the corridor through an open doorway, air transfer grille, or other opening. The critical velocities from this relation are indicative of the kind of air velocities required to prevent smoke backflow from fires of different sizes. Thomas' equation can be used to estimate the airflow rate necessary to prevent smoke backflow through an open door in a boundary of a smoke control system.

Huggett's Constant

To evaluate the oxygen supplied to the fire, research underlying the development of oxygen consumption calorimetry can be used. Huggett (1980) evaluated the oxygen consumed for combustion of numerous natural and synthetic solids. He found that, for most materials involved in building fires, the energy released per unit of mass of oxygen consumed is approximately 13.1 MJ/kg (5,630 Btu/lb). Air is 23.3% oxygen by weight. When all the oxygen in a kilogram of air is consumed, 3.0 MJ of heat are liberated. (When all the oxygen in a pound of air is consumed, 1,300 Btu of heat are liberated.)

Example

Consider a room fully involved in fire releasing 2.4 MW (8×10^6 Btu/h) of heat. The Thomas equation indicates that a velocity of about 4 m/s (800 fpm) is needed to prevent smoke backflow through a 0.9 m (3 ft) wide doorway. For a doorway area of 2 m^2 (22 ft^2), this amounts to about 8 m^3/s (16,000 cfm). If all the oxygen in this airflow were consumed in a fire, 28 MW (94×10^6 Btu/h) of heat is released. This means that the airflow needed to stop smoke from a fully involved room fire has the ability to support a fire about 10 times as large as the room fire.

It should be noted that a fully involved room fire of 2.4 MW (8×10^6 Btu/h) would probably be *ventilation controlled.* This means that the heat release rate of the fire would be restricted by airflow into the room, and an increase in airflow would result in increased burning.

Caution About Airflow

As can be seen from the above examples, the air needed to prevent smoke backflow can support an extremely large fire. In most commercial and residential buildings, sufficient fuel (paper, cardboard, furniture, etc.) is present to support very large fires. Even when the amount of fuel is normally very small, transient (short-term) fuel loads (during building renovation, material delivery, etc.) can be significant. Therefore, the ASHRAE smoke control design book recommends that airflow not be used to control smoke flow, except when the fire is suppressed or in the rare cases when fuel can be restricted with confidence.

FUTURE DIRECTION

The focus of fire research is changing from pressurization systems to atria and smoke management components. In general, our understanding of pressurization systems is well developed, and it seems that research in this area will decrease. However, research is needed to determine how to ensure the effectiveness of atria exhaust, the impact of sprinklers on atria smoke movement, and the extent to which plume theory developed from small-scale fires is applicable to atria systems. An ASHRAE-funded project examining the performance of fire dampers subjected to airflow at elevated temperatures is nearing completion, and further projects concerning system components may follow.

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DISCUSSION

David Waldman, The Conserver Group, Inc., Winnipeg, MB, Canada: ASHRAE's book on smoke control references a computer program (ASCOS). How could I obtain a copy of it?

John H. Klote: The computer program ASCOS is in the public domain. If you know someone with a copy, you are free to make a copy for yourself. It is also available from the Building and Fire Research Bulletin Board System (BFRBBS). BFRBBS is a computer system that communicates with other computers over the telephone lines. There is no cost for using BFRBBS other than the cost of the phone call. The phone number of BFRBBS is (301) 990-2272. The system operators are Nora Jason (301-975-6862) and Phyllis Martin (301-975-6669).